Performance evaluation of residential ventilation systems based on multi-zone ventilation models.

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ABSTRACT: This paper presents simulation results of the performance of different ventilation systems in 5 types of dwellings designs both with common and improved building air tightness. Dwelling types include detached houses, terraced houses and apartment flats. Two major types of ventilation systems are investigated: natural ventilation with passive stacks and mechanical exhaust systems. The systems are all sized according to the Belgian Ventilation Standard. The simulation results give an indication of differences in performance between the of systems. The multizone infiltration and ventilation simulation model COMIS is used to calculate the indoor air quality and the ventilation heat loss achieved by each system. Carbon-dioxide is used as an indicator for indoor air quality. Therefore the variation of carbon-dioxide concentration in response to predetermined occupation schedules is calculated. The paper presents the model premises and discusses the results of the simulations. The performance of the ventilation systems is related to the dwelling typology and the building air tightness. The results show that the natural ventilation systems and the systems with mechanical exhaust may not guarantee a sufficient indoor air quality in all rooms at all times.

1 INTRODUCTION

In the past decade the demands on energy performance of buildings have strengthened. As a result of this the need to incorporate designed ventilation systems into dwellings has increased and is often imposed by regulations. Ventilation may be achieved by means of natural ventilation systems or by a mechanically driven system. In countries with a moderate climate as Belgium, the Netherlands, France and the UK, simple passive stack and mechanical exhaust systems dominate the market (De Gids 2003, Durier 2008). The systems typically consist of trickle ventilators in habitable rooms (living room, bedroom, study,…) and passive stacks or extract fans in 'wet' rooms (kitchen, bathroom,…), in combination with transfer openings in doors. The various components are sized according to general guidelines described in national standards. Although the climate and thus the driving forces for natural ventilation are rather similar, the directions in the standards diverge. This is the result of different assumptions about building air tightness and user behaviour.

As an example Table 1 shows the minimal extract flow rates required in utility rooms. Table 2 shows the minimal effective leakage area of a trickle ventilator achieving the required supply flow rates for fresh air. Although the sizing of the system components in the different countries may differ up to a factor 4 (see Table 2), the standards all claim that the guidelines ensure the required flow rates for indoor air quality in dwellings in a controlled way. At least the comparison learns that there is no consensus on how natural ventilation systems in dwellings should be designed, and that there is room for optimization.

Table 1: Design extract flow rates (m³/h)

Function	B	Nl	F	UK
Kitchen	50	75	120	47
Bathroom	50	50	30	29
Toilet	25	25	15	22

Table 2: Minimal leakage area of vent in a 12 m² bedroom

	B	Nl	F	UK
Design flow rate	1.0 l/s/m²	0.7 l/s/m²	30 m³/h	0.3 l/s/m²
Design pressure difference	2 Pa	1 Pa	10 Pa	-
Effective leakage area	108 cm²	107 cm²	34 cm²	25 cm²/ 50 cm² *

* Lower value for mechanical extract, higher for passive stack systems

Table 3: Classification IAQ according to EN 13779

Category	Quality	CO_2-level above outdoor
IDA1	High	≤ 400 ppm
IDA2	Medium	400-600 ppm
IDA3	Moderate	600-1000 ppm
IDA4	Low	> 1000 ppm

As a first step to develop performance based guidelines for residential ventilation systems, the effective performance of systems that meet the current standards should be evaluated. Of course, the performance depends on dwelling typology, air tightness, user behaviour, etc... The relation between these different parameters and the resulting indoor air quality is often analysed by means of numerical simulation (Jreijiry et al. 2007, Maeyens & Janssens 2003, Hayashi et al. 2001). Indoor air quality may be assessed by means of different criteria, depending on the pollutants to be removed by the ventilation system. An often used criterion for residential ventilation is based on occupant exposure to metabolic CO_2-concentration as an indicator for increased odour intensities. This is the case for assessment methodologies developed in the Netherlands and France (Van Den Bossche et al. 2007). The European standard EN 13799 presents a classification of indoor air quality into four categories by CO_2-level. This classification is well established for occupied rooms where pollution is caused mainly by human metabolism. Although the categories have been developed for non-residential buildings, the definition also applies to living rooms and bedrooms. Table 3 shows the limits between the classes.
In the following the performance of passive stack and mechanical exhaust systems is evaluated by means of numerical simulation using the IAQ-classification presented in Table 3. The systems are all sized according to the Belgian Ventilation Standard NBN D50-001. The analysis is done for 5 types of dwelling designs both with common and improved building air tightness.

2 REFERENCE DWELLINGS

The reference dwelling designs have been developed in the framework of a research project on the optimisation of building envelope and services for low-energy residential buildings (Verbeeck & Hens, 2007). The five dwellings are all single family houses with the same programme (family with 4 persons) and the same useful floor area corresponding to national statistical figures. All houses comprise a living room, 3 bedrooms, kitchen, bathroom, toilet, utility room, and hall way, with a total net floor area of about 150 m². In the detached and terraced house also a study room is present. The dwellings further differ in typology and building compactness, ranging from a detached bungalow to a flat in a 6-floor apartment building, representative for Belgian construction practice. The market share of newly built dwellings during the last decade in Belgium is typically 40% detached houses, 40% apartments and 20% terraced or semi-detached. Table 4 gives a survey of geometrical characteristics of the five reference dwellings.

The ventilation systems are sized according to the minimal requirements in the Belgian ventilation standard. They consist of:

– Trickle ventilators in all habitable rooms sized in order to supply 3.6 m³/h per m² floor area at a 2 Pa pressure difference. The total design flow rate for supply of fresh air is listed in Table 4. These flow rates are suffcicient to achieve a high IAQ (IDA 1) under normal occupation.
– Passive stack units or extract fans, sized in order to extract the design flow rates listed in Table 1. For passive stacks the design flow rate is achieved at a pressure difference of 2 Pa. The total extract flow rate is listed in Table 4.
– Transfer openings with a free section of 70 cm² in at least one internal door per room, necessary to transfer 25 m³/h at a 2 Pa pressure difference; the transfer opening in the kitchen door has a section of 140 cm².

Since the number of rooms and the floor area of all houses is roughly the same, also the design flow rates for the 5 houses are similar. As the table shows design flow rates for supply are typically larger than extract flow rates according to the Belgian Ventilation Standard.

The building site of the detached houses is supposed to be roughly open, the semi-detached house and apartment are located in an urban landscape, while the terraced house is in a closed city landscape. These assumptions define the local wind exposure of the houses, which affects ventilation performance.

Table 4: Geometrical characteristics of reference dwellings

	Bungalow	Detached	Semi-detached	Terraced	Apartment
Compactness	0.9 m	1.3 m	1.6 m	2.1 m	3.8 m
Heated volume	557.3 m³	528.7 m³	521.0 m³	493.6 m³	450.0 m³
Heat loss area	611.3 m²	395.4 m²	330.1 m²	231.9 m²	118.4 m²
Number of floors	1	2	2	3	1 (of 6)
Design supply	329 m³/h	350 m³/h	325 m³/h	346 m³/h	318 m³/h
Design exhaust	175 m³/h	200 m³/h	200 m³/h	200 m³/h	200 m³/h
Shielding	Open	Open	Normal	Shielded	Normal
Façade direction	north	east	east	north	south

3 VENTILATION MODEL

The multi-zone infiltration and ventilation simulation model COMIS is used to calculate the indoor air quality and the ventilation flow rates achieved by each system (Feustel 1999). The basic assumption in multi-zone modeling is that the air in a single zone is well mixed, such that the zone conditions (air pressure, temperature, pollutant concentration) are equal in the whole zone. The reference dwellings are represented by as many zones as there are rooms in the house. This results in ventilation models with 9 to 10 zones, connected to other internal zones and the external environment by air flow paths, representing the ventilation system components and air leakage paths.

3.1 *Occupancy schedules*

A household with two adults and two children is considered here, with one adult and one child under the school-age staying at home. The proposed occupation represents a rather large pollutant load, given that the size of a household in Belgium is 2.4 persons on average, and that twenty percent of the Belgian households consist of 4 persons or more (NIS 2004). The occupancy profile and the related emission of contaminants (in this study CO_2) is based on data from IEA Annex 27 (Mansson 1995). There is a different occupancy schedule for week- and weekend days.

The CO_2 emission flow rates are calculated according to the default procedure in COMIS, which relate emission rates to metabolism and age of occupants. The metabolism is scheduled to vary between 0.8 Met during sleeping up to 1.7 Met during domestic activities (washing, cooking,…). The CO_2 generation rate at 1 Met is 18 l/h per adult. At this generation rate the required ventilation should be 18 m³/h per person in order to achieve a sufficient indoor air quality (IDA 3 or better, see Table 3).

The schedules with set-point temperatures are in line with the occupancy profiles per room. The temperatures are not calculated in a transient way in COMIS but are given as time-dependent input-values. Consequently the set-point temperatures are considered as the effective air temperatures that define the thermal stack pressures. Air temperature during the day in the living room and in the evening in the bed rooms is set at 21°C. The temperature for night-time set-back is 15°C. The volume and time averaged temperature in the reference dwellings is approximately 18°C, which is the mean indoor temperature taken into account in energy performance calculations for residential buildings in Belgium.

3.2 *Boundary conditions*

Weather data are taken from the Test Reference Year for Uccle, Belgium, with hourly mean values for temperature, wind speed and wind direction. During the heating season (October-April) the mean temperature and meteorological wind speed are 6.1°C and 4.1 m/s, respectively. Prevailing winds are from the southwest.

The chosen wind shielding conditions presented in Table 4 have an effect on both the local wind velocity profile and the value of wind pressure coefficients which are used to calculate wind induced pressures. The wind velocity profile is described by means of the power law wind profile as a function of height (Feustel 1999). The profile exponent at the dwelling location has a value of 0.22 for open country, 0.25 for normal shielding in the suburbs and 0.35 for shielded urban conditions.

Wind pressure coefficients corresponding to the chosen shielding conditions are taken from tables reported by AIVC (Orme & Leksmono 2002).

3.3 *Air leakage paths*

To analyse the relation between ventilation system performance and air tightness, the simulations are made for different levels of the building air tightness:

- Typical building air tightness measured during a survey in newly built Belgian dwellings (Bossaer et al. 1998). Measurements showed a poor air tightness in current construction practice with average n_{50}-values of 9.5 h^{-1} for detached houses, 8.3 h^{-1} for semi-detached houses, 5.3 h^{-1} for terraced houses and 4.1 h^{-1} for apartments. These values correspond to an envelope air permeance of about 9 m³/h per m² outer envelope area at 50 Pa pressure difference.
- Improved air tightness levels of 3.0 h^{-1}, 1.0 h^{-1} (recommended values for energy efficient ventilation in Belgian ventilation standard) and 0.6 h^{-1} (passive house standard).

Based on observations by Bossaer et al. (1998) air leakage paths are assumed to be distributed over exterior walls and roof surfaces. The ratio between the area specific air leakage rate in the roofs and walls is supposed to be 2/3. Starting from the n_{50}-value under consideration and the assumptions on leakage distribution, air leakage is simulated by means of cracks.

Leakage in each envelope part of a room with different orientation or slope is subdivided over two cracks. One crack is located at a quarter of the total room height, the other at three quarter. The flow coefficients of the cracks are taken proportional to the wall area, in such a way that the combination of all cracks results in an overall building air tightness equal to the chosen n_{50}-value. Crack flow is modelled by means of a power law flow equation with exponent 0.67. The methodology presented in this section is in agreement with guidelines given in prEN 15242 (2006).

3.4 *Ventilation components*

The trickle ventilators in the habitable rooms are sized to provide the design flow rate at a pressure difference of 2 Pa (see § 2). Two different types of trickle ventilators are analyzed. The first is a normal vent with a flow characteristic following the power law flow equation according to Equation 1.

$$\dot{V} = \dot{V}_{ref} \sqrt{\Delta p / \Delta p_{ref}} \qquad (1)$$

where V_{ref} is the design flow rate and Δp_{ref} is the design pressure difference of 2 Pa.

The second type is a so-called self-regulating or pressure-regulating ventilator, where the flow rate achieved at pressure differences above 2 Pa stabilizes to a constant value. For this purpose a one-way damper is installed in the ventilator flow path. The Flemish Energy Performance Regulation proposes a classification for self-regulating ventilators, depending on how much the flow rate deviates from the design flow rate (F.Gov. 2005, Willems & Janssens 2005). In this study a so-called P4-vent is considered with a deviation between the flow characteristic and the design flow rate smaller than 20%.

Figure 1 shows the measured flow characteristics of a normal and P4-ventilator, together with the upper limit of the P4-class. In this study the upper limit is used to model the flow characteristic. This means the flow reaches a constant value at pressure differences above 2.9 Pa between outside and inside. The self-regulating property is only active when the outside pressure is larger than the inside pressure (ingoing flow). At negative pressure differences (outgoing flow) the self-regulating vent behaves as a normal ventilator and is modeled as such.

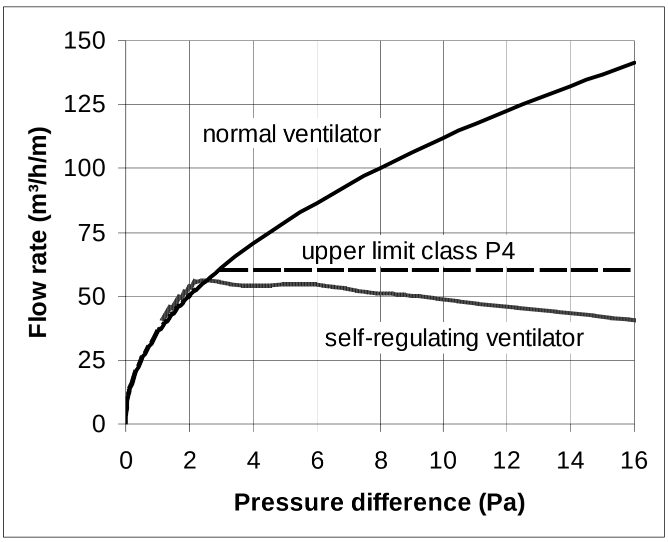

Figure 1: Flow characteristics for normal and self-regulating ventilators with design flow rate of 50 m³/h/m.

3.5 *User interaction*

The aim of this study is to evaluate the achievable indoor air quality of ventilation systems, regardless of how they are used by occupants or how occupants provide in additional airing by opening windows. Therefore it is assumed that the systems are used to their maximum design capacities. This means that manual adjustments of ventilation components, such as closing trickle vents or switching fans to lower speeds, are not taken into account, although these actions are allowed for in the design of these systems.

For the same reason the use of windows and doors is not taken into account. This assumption is further based on German field investigations showing that the use of windows in dwellings is limited in winter (Erhorn et al. 2001). The same investigation learns that the frequency of opening windows stays the same independent of the type of ventilation system installed (natural or mechanical). These findings show that during the heating season indoor air quality is primarily dependent on the performance of the ventilation system present. This justifies the chosen approach to disregard user interaction in the analysis of ventilation system performance. Consequently only the simulation results for the heating season will be taken into account (October-April).

4 RESULTS

4.1 *Achievable IAQ in different rooms*

The performance of the ventilation systems differs from room to room. To illustrate this, Figures 2 and 3 show the distribution of exposure hours to a certain IAQ-class in the different habitable rooms. Since the trends are similar for the different cases the results of the semi-detached house with airtightness n_{50} of 3.0 h^{-1} are used here as an example. Figure 2 relates to the passive stack system, Figure 3 to the mechanical exhaust system. The exposure hours are based on the exposure during the time of occupation of a room.

In general a high to moderate IAQ (IDA 1 to 3) is achievable in the living room, while in the bed rooms an acceptable IAQ may not be achievable during part of the occupation time (IDA 4). The exposure to low IAQ occurs most often in the master bedroom (bedroom 1), because of the double number of occupants. Low IAQ occurs because the effective pressure differences resulting from wind and thermal stack are generally smaller than the design pressure difference of 2 Pa. Furthermore the limited size of transfer openings restricts the flow from one room to another. Hence the design flow rates in the habitable rooms are usually not met, both in the passive stack as the mechanical exhaust system.

Figure 2: Distribution of IAQ in semi-detached house with passive stack system and self-regulating ventilators (n_{50} = 3.0 h^{-1}).

Figure 3: Distribution of IAQ in semi-detached house with mechanical exhaust and self-regulating ventilators (n_{50} = 3.0 h^{-1}).

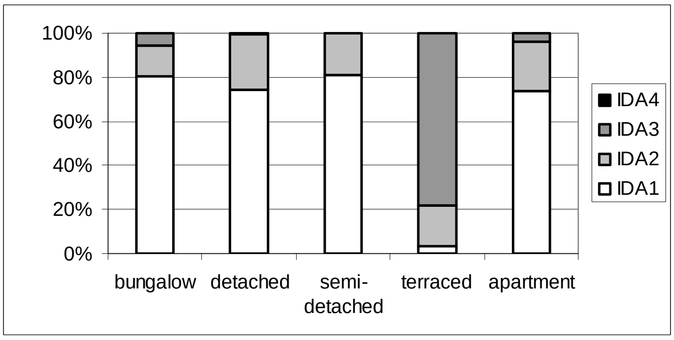

Figure 4: Distribution of IAQ in living rooms of dwellings with mechanical exhaust and self-regulating ventilators (n_{50} = 3.0 h^{-1}).

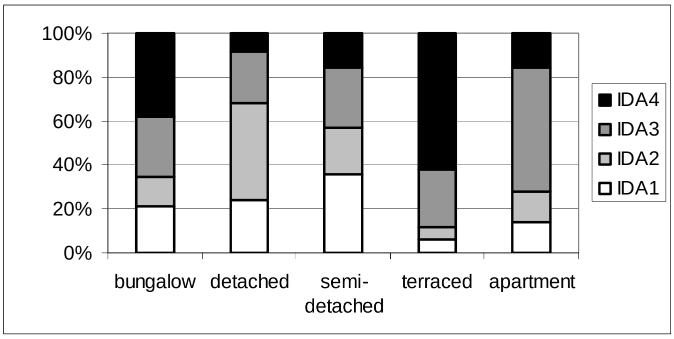

Figure 5: Distribution of IAQ in master bed rooms of dwellings with mechanical exhaust and self-regulating ventilators (n_{50} = 3.0 h^{-1}).

The presence of mechanical extraction in the 'wet' rooms has a positive influence on the IAQ in habitable rooms. Mechanical extraction may assist ventilation in the habitable rooms at times when wind speeds or temperature differences are low. However an acceptable IAQ is still not achievable at all times in the bed rooms. This shows that also with mechanical exhaust systems the natural driving forces dominate the ventilation performance in habitable rooms. Of course because of mechanical extraction, the removal of pollutants from the wet rooms is more efficient compared to passive stack systems, but this quality is not detected by the performance indicator chosen in this study.

4.2 *Influence of dwelling typology*

The performance of ventilation systems further depends on dwelling typology and shielding. Figures 4 and 5 show the distribution of exposure hours to a certain IAQ-class in the living rooms and master bed rooms of the five reference dwellings with mechanical exhaust systems. Although the systems are designed on the same basis with similar design flow rates (see Table 4), the achievable IAQ in the different dwellings is different. The occurrence of a good IAQ is the smallest in conditions with minor wind or thermal stack pressures, eg the bungalow and apartment (one floor) and terraced house (shielded wind conditions). Exposure to poor IAQ also occurs more often in rooms with a single exposed façade, since cross ventilation from windward to leeward side of the room is not possible (terraced house and apartment). Furthermore, in some rooms the different driving forces (wind, thermal stack and mechanical exhaust) may oppose each other. This is for instance the case in rooms on the top floor located on the windward side of the building. As a result, flow rates through ventilators may deviate substantially from design flow rates at some times.

4.3 *Influence of building airtightness*

Since exposure to a low IAQ occurs most often in the master bedrooms, the influence of building air tightness is illustrated for this room. Figure 6 shows the relative occurrence of low IAQ during occupation for passive stack systems with self-regulating vents. As expected IAQ improves when the building envelope is more leaky and deteriorates with better air tightness. This relation is less prominent in dwelling types where the bed room has only a single exposed façade, such as the terraced house and apartment. In the terraced house the achievable IAQ in the master bed room is even independent of air tightness. The reason for this is the location of the master bed room at the middle floor of 3 floors close to the neutral pressure plane.

The influence of building air tightness is less straightforward for mechanical exhaust systems, as Figure 7 demonstrates. In the detached and semi-detached house the influence is similar as with passive stack systems. In the terraced house, bungalow and apartment, the trend is opposite: IAQ improves when the building becomes more air tight. This is due to the fact that a better building air tightness has a double effect. On the one hand the air leakage rates as a result of wind and thermal stack diminish, as in passive stack systems. On the other hand the underpressure in the building achieved by the mechanical exhaust becomes larger and the flow rates through the trickle ventilators increase. Depending on which effect dominates, the IAQ may either decrease or improve as a function of air tightness.

The trends observed above are also present when air flow rates are considered. Figure 8 shows the total flow rate of outdoor air entering a dwelling, either through ventilation components or cracks, averaged over the heating season. For reasons of clarity only the results for the detached house and the apartment are represented. The total air flow rate is composed of air infiltration through the building envelope and dedicated ventilation through system components. As a result the total air flow rate depends almost linearly on building air tightness n_{50}. In dwellings with shielded wind conditions the dependency is smaller. The presence of a large number of partition walls with constraining transfer openings between windward and leeward facade, like in the apartment, has a similar effect. The total air flow rate is also less dependent on building air tightness in mechanical exhaust systems. This is because the flow rates are mechanically assisted. At n_{50}-values smaller than 1.0 h-1, the total fresh air flow rate approaches the design flow rate for mechanical extraction of 200 m³/h. This suggests that in these conditions exhaust ventilation is able to maintain a permanent underpressure in all rooms of the dwelling, thus forcing the air along the design air flow path from habitable rooms to 'wet' rooms and avoiding backdraft.

4.4 *Influence of self-regulating ventilators*

Simulation results show no significant differences between achievable IAQ with normal or self-regulating ventilators. This is logical, since poor IAQ occurs at conditions when pressure differences and consequently flow rates across inlet vents are small. As Figure 1 shows the flow characteristics of normal and self-regulating ventilators at pressure differences below 2.9 Pa are similar.

However when high pressure differences are available, self-regulating ventilators avoid excessive ventilation. This results in a reduction of the total fresh air flow rate and ventilation heat loss. The reduction ranges from 15% at exposed locations to wind (detached house) to 1 or 2% at shielded locations or in building typologies with single exposed facades (terraced house and apartment).

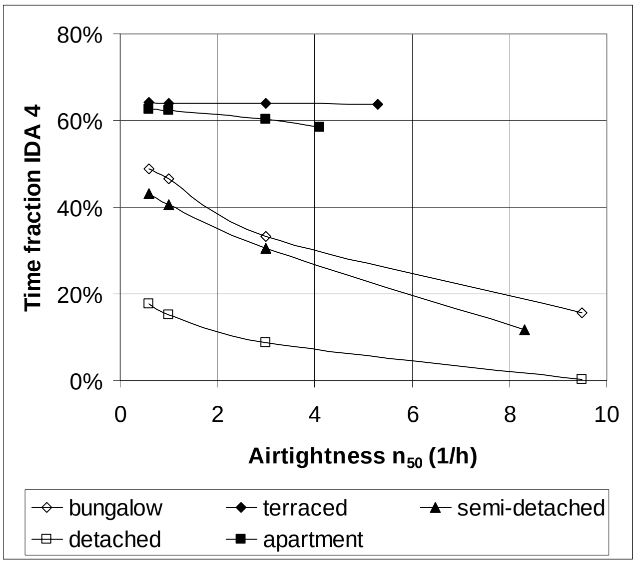

Figure 6: Time fraction with low IAQ during occupation time of master bed room as a function of building airtightness: passive stack systems with self-regulating ventilators.

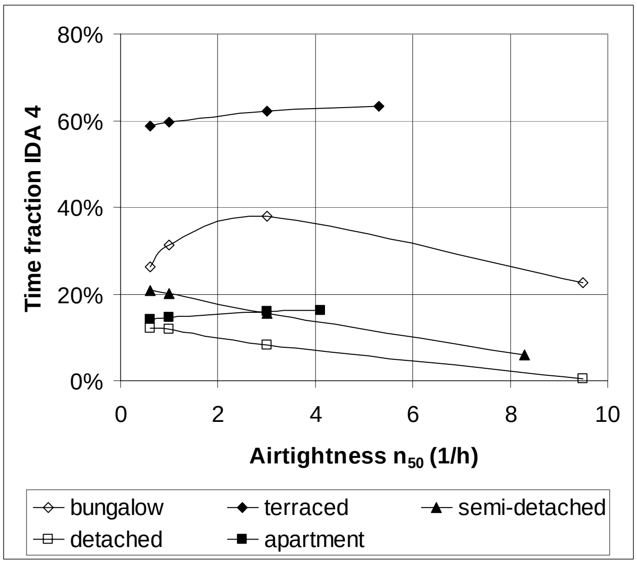

Figure 7: Time fraction with low IAQ during occupation time of master bed room as a function of building air tightness: mechanical exhaust systems with self-regulating ventilators.

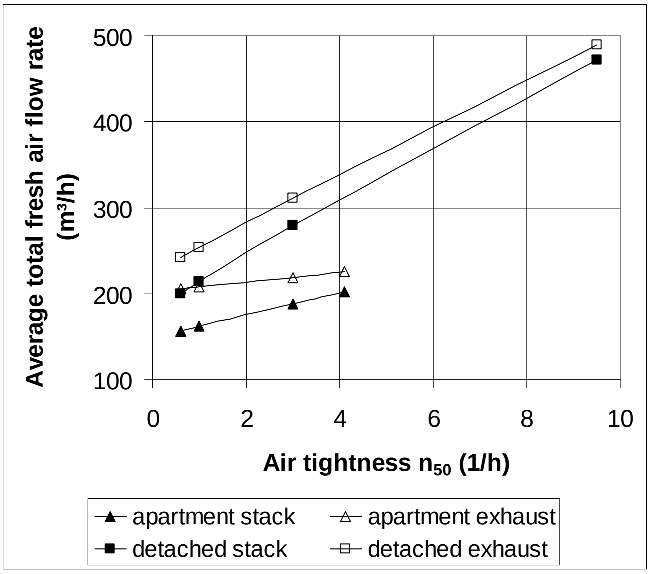

Figure 8: Total fresh air flow rate, averaged over the heating season, as a function of building air tightness.

5 CONCLUSIONS

This paper presented simulation results of the performance of different ventilation systems in 5 types of dwelling designs. Dwelling types included detached houses, terraced houses and apartment flats. Two major types of ventilation systems were investigated: natural ventilation with passive stacks and mechanical exhaust systems. The systems were all sized according to the Belgian Ventilation Standard. The simulation results showed a large difference in achievable indoor air quality from room to room and a strong dependency on dwelling typology and shielding. Natural ventilation systems and systems with mechanical exhaust may not guarantee a sufficient indoor air quality in all rooms at all times. The presence of mechanical exhausts in 'wet' rooms however improved the achievable IAQ in habitable rooms.

The interaction between system performance and building air tightness was different for both systems. With mechanical exhaust systems improved building air tightness may at the same time reduce ventilation heat loss and advance achievable IAQ. Finally the results showed that the use of self-regulating ventilators may reduce ventilation heat loss by a maximum of 15% without jeopardizing IAQ.

The performance analysis of ventilation systems sized according to the Belgian standard showed that there is room for improvement. According to a comparison of existing standards there are also large differences in design rules between European countries. A further study will try to optimize the existing regulations for sizing residential ventilation systems on a performance basis by developing a multi-parameter performance criterion (Laverge & Janssens 2008).

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